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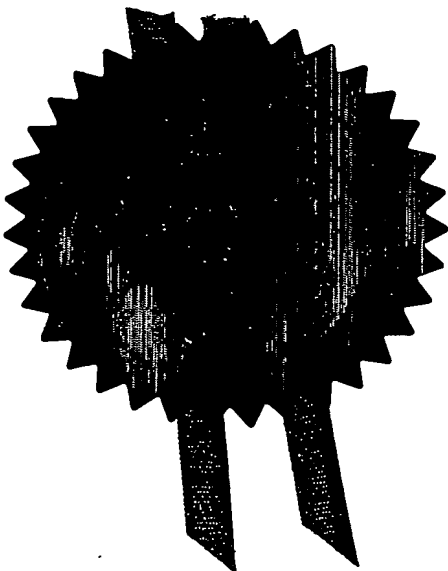
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Signed *A. B. Jones*

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0222252.9

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SOUTHAMPTON PHOTONICS LIMITED
PHI HOUSE
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CHILWORTH SCIENCE PARK
SOUTHAMPTON
SO16 7ND

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation **ENGLAND**

07894330002

4. Title of the invention

AN OPTICAL FIBRE

5. Name of your agent (if you have one)

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

Graham Jones + Co.
77 Beaconsfield Rd.
Blackheath
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SE3 7LG

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Country

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11.

I/We request the grant of a patent on the basis of this application.

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AN OPTICAL FIBRE

Field of Invention

This invention relates to an optical fibre for high-power lasers and amplifiers.

Background to the Invention

Stimulated Brillouin Scattering (SBS) provides a limitation for high-power fibre lasers and optical amplifiers. Light travelling down the fibre excites an acoustic wave which reflects the light, the reflected light being shifted in wavelength by the Brillouin wavelength shift. Different glass materials have different Brillouin wavelength shifts and Brillouin bandwidths.

It is known that the SBS threshold can be increased by varying the materials along an optical fibre, by inducing a temperature gradient along a fibre, and by utilizing glasses having different Brillouin shifts across the cross section of a fibre.

It is also known that the SBS threshold can be increased using so-called large mode area fibres — for example see WO 00/02290. Such fibres can have relatively low numerical apertures and can be operated multi-moded and bent such as to provide higher losses for the higher-order modes as compared to the fundamental mode.

There is a need for a fibre that can be used in single-frequency lasers and amplifiers and that has a high SBS threshold. It is preferred that the fibre is linearly birefringent and can be operated in a single polarization regime.

It is an aim of the present invention to increase the stimulated Brillouin scattering threshold of an optical fibre.

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Summary of the Invention

According to a non-limiting embodiment of the present invention there is provided an optical fibre comprising a waveguide and at least one stress applying region, in which the waveguide is defined by a numerical aperture, the stress applying region has a depressed refractive index, and in which the optical fibre is configured such that the waveguide supports at least two polarised fundamental modes, two polarised first second-order modes, and two polarised second second-order modes, and in which the waveguide comprises a gain medium, and in which the stress applying region, the waveguide and the disposition of the gain medium are such as to provide preferential guidance to at least one of the fundamental modes at an operating wavelength.

The optical fibre may be bent.

The gain medium may comprise one or more rare-earth dopant.

The rare earth dopant may comprise one or more of Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium, Europium, Terbium, and Dysprosium.

At least one of the fundamental modes, the first second-order modes, and the second second-order modes may be leaky at the operating wavelength.

The optical fibre is preferably configured to operate as a single-polarisation optical fibre at the operating wavelength.

The optical fibre may be tapered along its length.

The waveguide may be tapered along its length.

The numerical aperture may correspond to an index difference less than around 0.0035.

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The numerical aperture may correspond to an index difference less than around 0.003.

The numerical aperture may correspond to an index difference less than around 0.0025.

The numerical aperture may correspond to an index difference less than around 0.002.

The optical fibre may comprise a photosensitive region.

The photosensitive region may be at least partly in the stress applying region.

The photosensitive region may be at least partly in the waveguide.

The optical fibre may be defined by a stimulated Brillouin scattering threshold, and the optical fibre may have been exposed to ultraviolet radiation at least partly along its length in order to increase the stimulated Brillouin scattering threshold.

The optical fibre may be defined by a stimulated Brillouin scattering threshold, and the optical fibre may have been exposed to heat treatment at least partly along its length in order to increase the stimulated Brillouin scattering threshold.

The invention also provides an optical amplifying device comprising the optical fibre. The optical amplifying device may be an optical amplifier, a laser, or a master oscillator power amplifier. In use, the optical amplifying device may emit optical radiation. The optical radiation may be pulsed, modulated or continuous wave.

The invention also provides an optical fibre comprising a waveguide having a depressed refractive index region and a gain medium, in which the waveguide is defined by two polarised fundamental modes, two polarised first second-order modes

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and two polarised second second-order modes, and in which the depressed refractive index region is configured to provide preferential guidance to the first second-order modes compared to the second second-order modes, and the gain medium is configured to provide preferential guidance to the fundamental modes compared to the first second-order modes.

The optical fibre may comprise at least one stress applying region.

The optical fibre may be configured to provide single-polarisation operation at an operating wavelength.

Brief Description of the Drawings

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 shows an optical fibre according to the present invention;

Figure 2 shows an optical fibre comprising two stress applying regions;

Figure 3 shows the fundamental modes of an optical fibre;

Figure 4 shows the second-order modes of an optical fibre;

Figure 5 shows transmission of an optical fibre with respect to wavelength;

Figure 6 shows the relative transmission of two polarisations in an optical fibre;

Figure 7 shows an operating window in which single-polarisation operation is achieved;

Figure 8 shows the variation in extinction ratio with wavelength and azimuth;

Figure 9 defines azimuth;

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Figure 10 shows the variation of wavelength with azimuth for a 15dB extinction ratio;

Figure 11 shows an optical fibre with a gain medium;

Figure 12 shows a refractive index variation of an optical fibre;

Figure 13 shows an optical fibre with photosensitive regions in the stress applying regions;

Figure 14 shows an optical fibre with photosensitive regions in the core;

Figure 15 shows an amplifying optical device;

Figure 16 shows an optical fibre comprising depressed index regions;

Figure 17 shows the refractive index profile of the fibre shown in Figure 17;

Figure 18 shows an optical fibre comprising longitudinally extending holes;

Figure 19 shows an optical fibre comprising a raised index ring around the core; and

Figures 20 to 23 show manufacturing steps to fabricate the fibre shown in Figure 13.

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Detailed Description of Preferred Embodiments of the Invention

With reference to Figure 1, there is provided an optical fibre 1 comprising a waveguide 2 and at least one stress applying region 3, in which the waveguide 2 is defined by a numerical aperture, the stress applying region 3 has a depressed refractive index, and in which the optical fibre 1 is configured such that the waveguide 2 supports at least two polarised fundamental modes, two polarised first second-order modes, and two polarised second second-order modes, and in which the waveguide 2 comprises a gain medium 4, and in which the stress applying region 3, the waveguide 2 and the disposition of the gain medium 4 are such as to provide preferential guidance to at least one of the fundamental modes at an operating wavelength.

The waveguide 2 can be a microstructured fibre containing longitudinally extending holes along its length.

The optical fibre 1 can be circular, oval, elliptical or have a rectangular cross-section. The optical fibre 1 is preferably coated.

Figure 2 shows a cross-section of an optical fibre 20 comprising a substrate 22, stress applying regions 21, a core 23 and an inner cladding region 24. The core 23 and inner cladding region 24 comprise the waveguide 2. The stress applying regions 21 are typically doped with boron or boron co-doped with germania and typically have a depressed refractive index with respect to the refractive index of the substrate 22. The substrate 22 is typically silica.

Figure 3 shows the x- and y-polarised fundamental modes 31, 32 of the fibre 20, labelled HE_{11}^x and HE_{11}^y respectively. The fundamental modes 31, 32 have a maximum amplitude located approximately at the centre of the core 23.

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Figure 4 shows the four second-order modes 41, 42, 43, 44 of the fibre 20. These can be separated into x- and y-polarised first second-order modes 41, 42 and x- and y-polarised second second-order modes 43, 44. The second-order modes 41, 42, 43, 44 have a minimum located approximately at the centre of the core 23.

Figure 5 shows the relative transmission 55 of the optical fibre 20 measured versus wavelength 56 of the optical fibre 20 when bent compared to when straight. Bending the optical fibre has the effect of increasing losses of modes that are operating near to cut off. The cut-offs of the four second modes 41, 42, 43, 44 are labelled as 51, 52, 53, 54 respectively. The depressed index of the stress applying regions 21 has the effect of reducing the cut-off wavelength of the second second-order modes 43, 44. The depressed refractive index region provides preferential guidance to the first second-order modes compared to the second second-order modes.

Figure 6 shows the relative transmission 61 of the optical fibre 20 measured versus wavelength 56 for x-polarised light compared to y-polarised light.

Figure 7 shows the relative transmission 76 of x- and y-polarised length versus wavelength 56 of a different length of the optical fibre 20, drawn to have a smaller diameter. The cut-off wavelengths 71, 72 of the two fundamental modes 31, 32, and the cut-off wavelengths 73, 74 of the two first second-order modes 41, 42 are identified.

Figure 8 shows the extinction ratio 81 of y-polarised light compared to x-polarised light measured through the optical fibre 20 as a function of wavelength 56 and azimuth θ 91 of the bend direction relative to the stress applying regions 21 as further defined in Figure 9. The wavelength variation 101 for a 15dB extinction is shown plotted against azimuth 91 in Figure 10. Figures 8, 9 and 10 demonstrate that

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the bend losses can be tuned by bending the optical fibre 20 and by controlling the azimuthal angle θ_1 of the bend radius.

Figure 11 shows an optical fibre 110 comprising two gain mediums 111. The gain medium 111 can comprise one or more rare-earth dopants. The rare earth dopant comprises one or more of Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium, Europium, Terbium, and Dysprosium. Preferably the rare earth dopant is Ytterbium or erbium. The erbium may be co-doped with Ytterbium. The disposition of the gain medium 111 is such that it provides preferential gain for the fundamental modes 31, 32 and the second second-order modes 43, 44 compared to the first second-order modes 41, 42. This is because the first second-order modes 41, 42 have a null along the x-axis. Thus when the optical fibre 20 is bent, the depressed index of the stress applying regions 21 will cause leakiness of the second second-order modes 43, 44, and the bend losses combined with the preferential gain afforded by the disposition of the gain medium 111 will cause additional leakage of the first second order modes as compared with the fundamental modes 31, 32.

Alternatively or additionally, the gain medium 4 can be located in the core 23 in a region where the intensity of the fundamental modes 31, 32 is greater than the intensity of the first second-order modes 41, 42.

Figure 7 shows a wavelength window 79 in which the optical fibre 20 operates as a single-polarisation optical fibre. A similar wavelength window will exist for the optical fibre 110. It is preferred that the optical fibre 110 is configured to operate as a single-polarisation optical fibre at its operating wavelength. This is achieved by appropriate choices of the refractive index profiles, relative dimensions and the fibre diameter.

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Figure 12 shows the refractive index profile 120 across the x-axis of the optical fibre 110. The refractive index of the core n_{co} 121 is raised with respect to the refractive index of the cladding n_{cl} 122. The refractive index of the stress applying regions 123 is depressed with respect to the cladding n_{cl} 122. The refractive index of the stress applying regions n_s 123 is typically depressed by about 0.0001 to 0.01 with respect to the refractive index of the cladding n_{cl} 122.

The refractive index n_{co} 121 is typically raised by about 0.001 to 0.005 with respect to the refractive index of the cladding n_{cl} 122. However, it may be advantageous to raise n_{co} 121 by 0.0005 to 0.001 with respect to the substrate 22 in order to reduce the numerical aperture of the fibre 110 further.

The refractive index difference between core and cladding is often expressed as a numerical aperture defined by $NA = (n_{co}^2 - n_{cl}^2)^{0.5}$.

In order to increase the Stimulated Brillouin Threshold, the numerical aperture should correspond to an index difference between core and cladding $n_{co} - n_{cl}$ less than around 0.0035. The numerical aperture can correspond to an index difference less than around 0.003. It is preferred that the numerical aperture corresponds to an index difference less than around 0.0025. Lower numerical apertures can also be advantageous, corresponding to refractive index differences of 0.002, or even 0.005 to 0.002.

The core 23 may comprise a more complex refractive index profile, including at least one ring and index depressions, the refractive index n_{co} 121 thus being interpreted as an effective refractive index – that is the equivalent refractive index of a conventional step-index fibre that guides light with the same spot size as would be guided in the optical fibre 110.

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further increases in the Stimulated Brillouin Threshold can be achieved by tapering the optical fibre 1 along its length. Additionally or alternatively, the waveguide 2 can be tapered along its length.

Figure 13 shows an optical fibre 130 comprising round stress applying regions 131. Such an optical fibre is typically referred to as a PANDA optical fibre. The design features of the optical fibre 130 are preferably similar to those described with reference to Figures 2 to 12, except that the stress applying regions 131 are approximately circular. The stress applying regions 131 comprise a photosensitive region 132. The photosensitive region 132 may be boron doped silica co-doped with germania.

Figure 14 shows an optical fibre 140 in which the core 23 comprises a photosensitive region 141. The photosensitive region may also be located wholly or partly in the core 23 and/or partly in the stress applying regions 131. Alternatively or additionally, the photosensitive region may be located in the inner cladding 24 or substrate 22. The photosensitive region 141 may be germania doped silica, or if located in the inner cladding 24 or substrate 22, germania silica co-doped with boron.

Exposing the optical fibre 130, 140 to ultraviolet light (for example as used in the manufacture of fibre Bragg gratings) or heat treating the optical fibre 130, 140 will change the stresses within the fibre cross-section and can increase the stimulated Brillouin scattering threshold. It is preferred that such irradiation or heat treatment is varied along the optical fibre 130, 140.

Figure 15 shows an optical amplifying device 150 comprising the optical fibre 153 and a source 151 of pump radiation 152. The optical amplifying device 150 may be an optical amplifier, a laser, or a master oscillator power amplifier. In use, the

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optical amplifying device may emit optical radiation 154. The optical radiation 154 may be pulsed, modulated or continuous wave.

It is preferred that in use the optical fibre 1 is bent. With reference to Figures 8, 9 and 10, it is seen that depending on the design of the optical fibre 1 single-polarisation operation at the operating wavelength of the optical amplifying device 150 can be achieved by varying the azimuth 91 of the optical fibre 1.

Figure 16 shows a cross-section of an optical fibre 160 having the gain medium 4 in the core 4. The optical fibre 160 also comprises a depressed cladding region 161 and two stress applying regions 162. The purpose of the depressed cladding region 161 is to cut-off the second second-order modes 43, 44 defined in Figure 7 and the purpose of the stress applying regions 162 is to induce stress birefringence and/or to create a window of single-polarisation operation 79 as defined in Figure 7. In certain embodiments of the present invention, the optical fibre 160 may have one or both of the depressed cladding regions 161 and stress applying regions 162.

Figure 17 shows the refractive index profile of the optical fibre 160. The core 4 has a raised index 170, the depressed cladding regions 161 a depressed index 172, and the stress applying regions 162 a depressed index 174 compared to the index 173 of the substrate 22. The refractive index 171 of the inner cladding 24 is approximately matched to the substrate 22. The index 174 of the stress applying regions 162 may alternatively be matched to the index 173 of the substrate 22, or may even be raised. It is preferred however to depress the index 174 of the stress applying regions 162.

Figure 18 shows an optical fibre 180 comprising longitudinally extending holes 181 instead of the depressed cladding regions 161 of Figure 16.

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Figure 19 shows an optical fibre 190 comprising two depressed-index regions 191 and a raised index ring 192 surrounding the core 141. Such a waveguide design comprising the core 141 and raised index ring 192 is a so-called large-mode area design - see United States Patent Application US 2002/0018630 A1 for more details. The core 141 may have a refractive index difference compared to the substrate 22 of around 0.001 to 0.002 and a diameter of around 15 μ m to 25 μ m. The ring 192 may have a raised index of around 0.0002 to 0.0007 compared to the substrate 22 and an outer diameter of around 40 μ m to 80 μ m.

Figure 20 shows the cross-section of an optical fibre preform 200 comprising a depressed index ring 201. The preform is sawn along the lines 202 to provide four longitudinally extending sections 203.

Figure 22 shows the cross-section of a optical fibre preform 210 comprising a raised-index ring 211. The preform 210 is sawn along the lines 212 to provide four longitudinally extending sections 213.

Figure 23 shows a rod-in-tube preform assembly 220 comprising a substrate 222 comprising holes 223 configured to accept the sections 203 and 213 and stress applying rods 221. The substrate 222 is preferably fused silica, and the holes 223 can be machined using ultrasonic drilling.

Figure 23 shows the resulting fibre 230 drawn from the preform assembly 220. The fibre 230 has gain regions 4 and depressed index regions 201 in the axis of the stress applying regions 191, and inner cladding 24 and positive index regions 211 in the perpendicular direction. The method of manufacture described with reference to Figures 20 to 23 is preferred to avoid preform shattering when highly-stressed regions are allowed to heat and cool.

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It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance performance.

The present invention extends to the above mentioned features taken singularly or in any combination.

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Claims

1. An optical fibre comprising a waveguide and at least one stress applying region, in which the waveguide is defined by a numerical aperture, the stress applying region has a depressed refractive index, and in which the optical fibre is configured such that the waveguide supports at least two polarised fundamental modes, two polarised first second-order modes, and two polarised second second-order modes, and in which the waveguide comprises a gain medium, and in which the stress applying region, the waveguide and the disposition of the gain medium are such as to provide preferential guidance to at least one of the fundamental modes at an operating wavelength.
2. An optical fibre according to claim 1 in which the optical fibre is bent.
3. An optical fibre according to claim 1 or claim 2 in which the gain medium comprises one or more rare-earth dopants.
4. An optical fibre according to claim 3 in which the rare earth dopant comprises one or more of Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium, Europium, Terbium, and Dysprosium.
5. An optical fibre according to any one of the preceding claims in which at least one of the fundamental modes, the first second-order modes, and the second second-order modes is leaky at the operating wavelength.
6. An optical fibre according to any one of the preceding claims in which the optical fibre is configured to operate as a single-polarisation optical fibre at the operating wavelength.
7. An optical fibre according to any one of the preceding claims in which the optical fibre is tapered along its length.

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8. An optical fibre according to any one of the preceding claims in which the waveguide is tapered along its length.
9. An optical fibre according to any one of the preceding claims in which the numerical aperture corresponds to an index difference less than around 0.0035.
10. An optical fibre according to any one of claims 1 to 8 in which the numerical aperture may correspond to an index difference less than around 0.003.
11. An optical fibre according to any one of claims 1 to 8 in which the numerical aperture may correspond to an index difference less than around 0.0025.
12. An optical fibre according to any one of claims 1 to 8 in which the numerical aperture may correspond to an index difference less than around 0.002.
13. An optical fibre according to any one of the preceding claims in which the optical fibre comprises a photosensitive region.
14. An optical fibre according to claim 13 in which the photosensitive region is at least partly in the stress applying region.
15. An optical fibre according to claim 13 in which the photosensitive region is at least partly in the waveguide.
16. An optical fibre according to any one of the preceding claims in which the optical fibre is defined by a stimulated Brillouin scattering threshold, and the optical fibre has been exposed to ultraviolet radiation at least partly along its length in order to increase the stimulated Brillouin scattering threshold.
17. An optical fibre according to any one of the preceding claims in which the optical fibre may be defined by a stimulated Brillouin scattering threshold, and the optical fibre may have been exposed to heat treatment at least partly along its length in order to increase the stimulated Brillouin scattering threshold.

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18. An optical fibre according to any one of the preceding claims configured as an optical amplifying device.
19. An optical fibre according to claim 18 in which the optical amplifying device is an optical amplifier, a laser, or a master oscillator power amplifier.
20. An optical fibre comprising a waveguide having a depressed refractive index region and a gain medium, in which the waveguide is defined by two polarised fundamental modes, two polarised first second-order modes and two polarised second second-order modes, and in which the depressed refractive index region is configured to provide preferential guidance to the first second-order modes compared to the second second-order modes, and the gain medium is configured to provide preferential guidance to the fundamental modes compared to the first second-order modes.
21. An optical fibre according to claim 20 and further comprising at least one stress applying region.
22. An optical fibre according to claim 20 or claim 21 which is configured to provide single-polarisation operation at an operating wavelength.
23. An optical fibre substantially as herein described with reference to the accompanying drawings.

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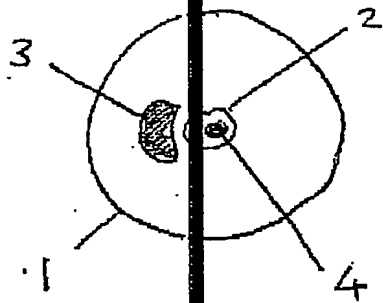


Fig 1

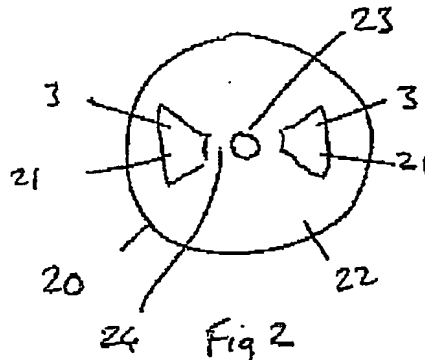


Fig 2

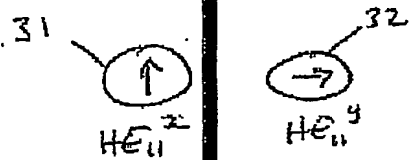


Fig 3

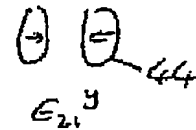
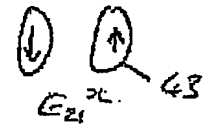
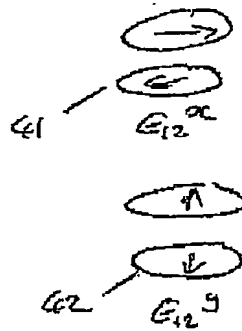


Fig 4

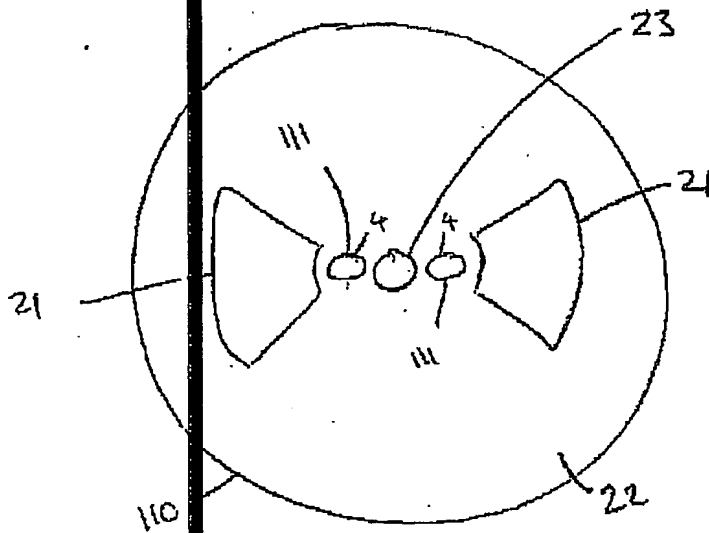


Fig 11

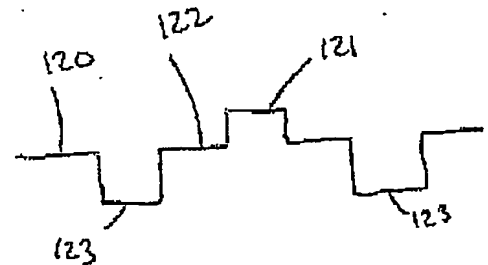


Fig 12

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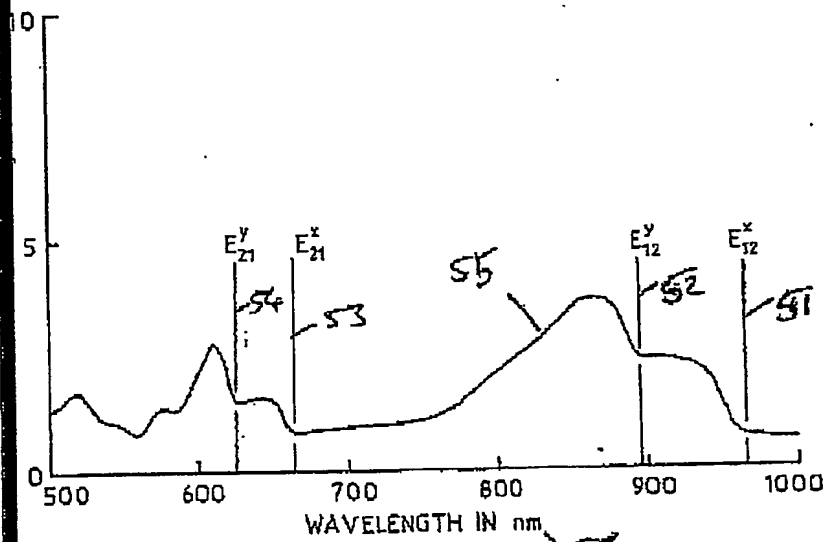


FIG 5

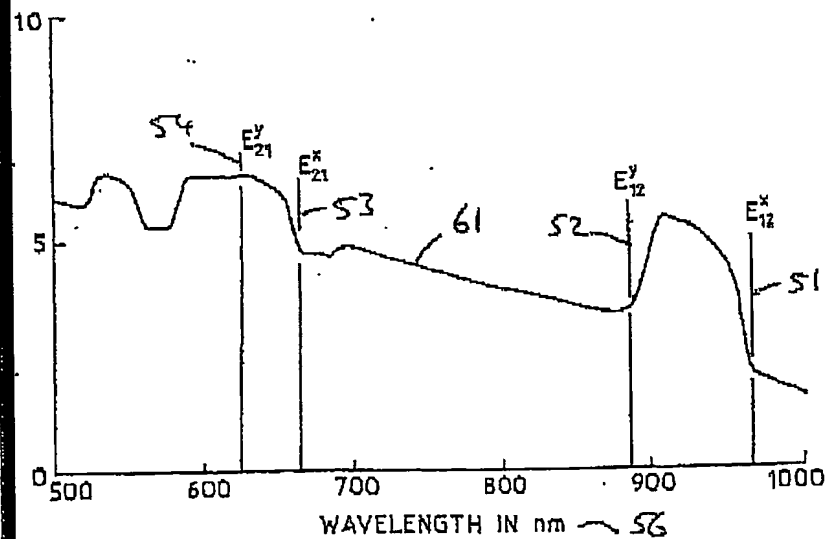


FIG 6

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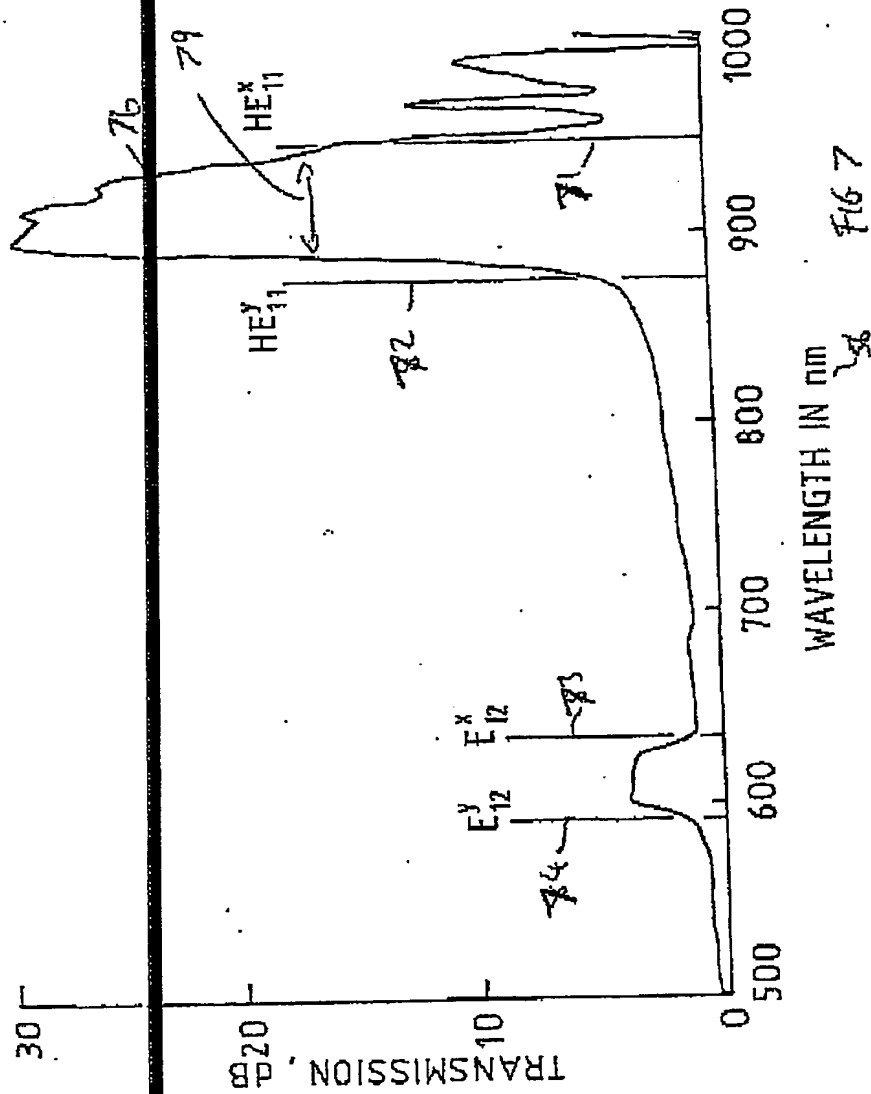


Fig 7

418

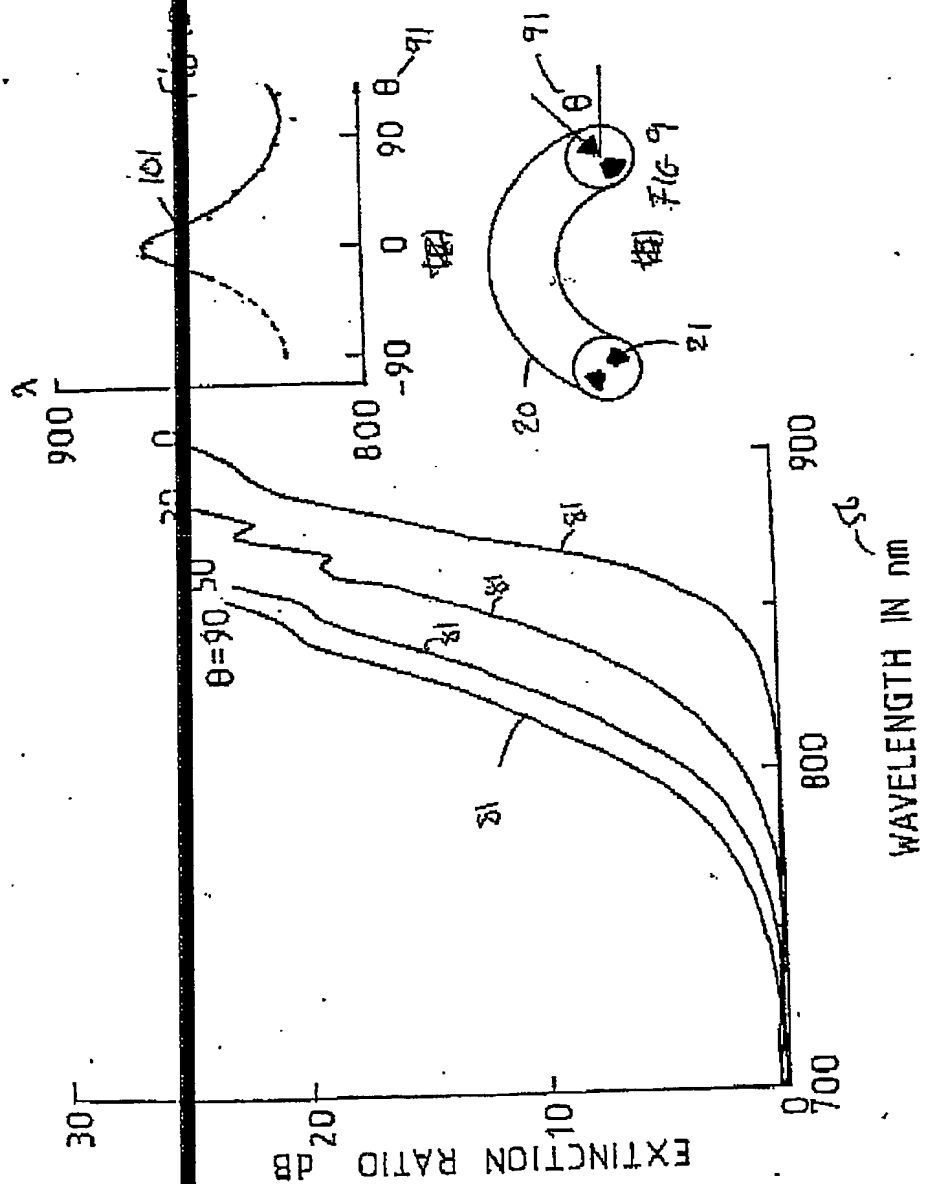


FIG 8

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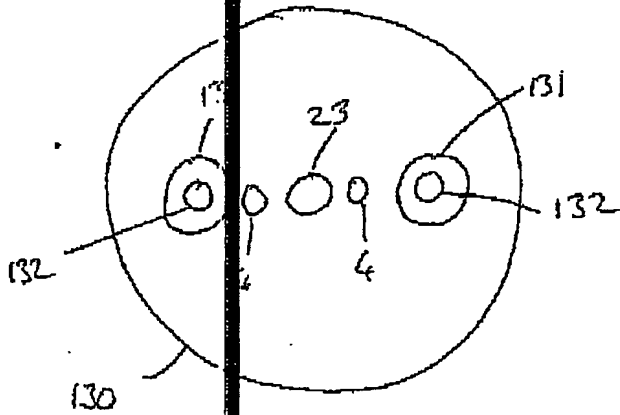


FIG 13

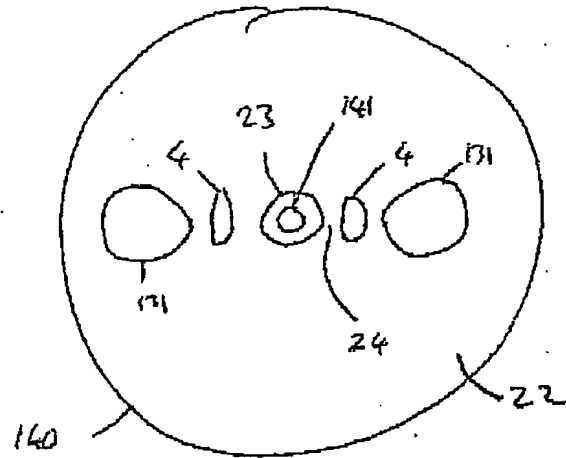


FIG 14



FIG 15

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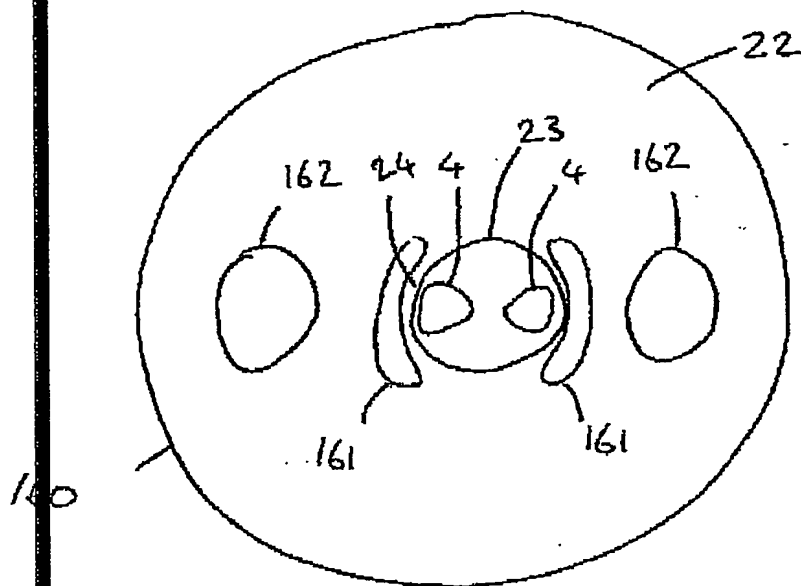


FIG 16

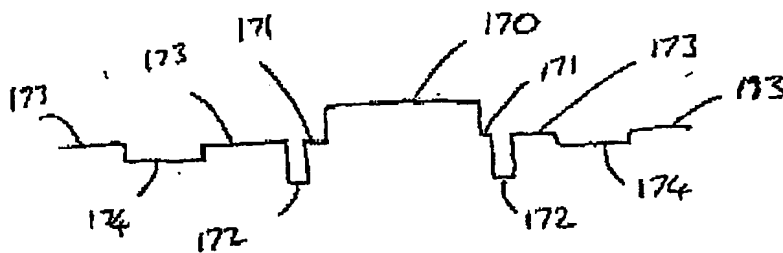


FIG 17

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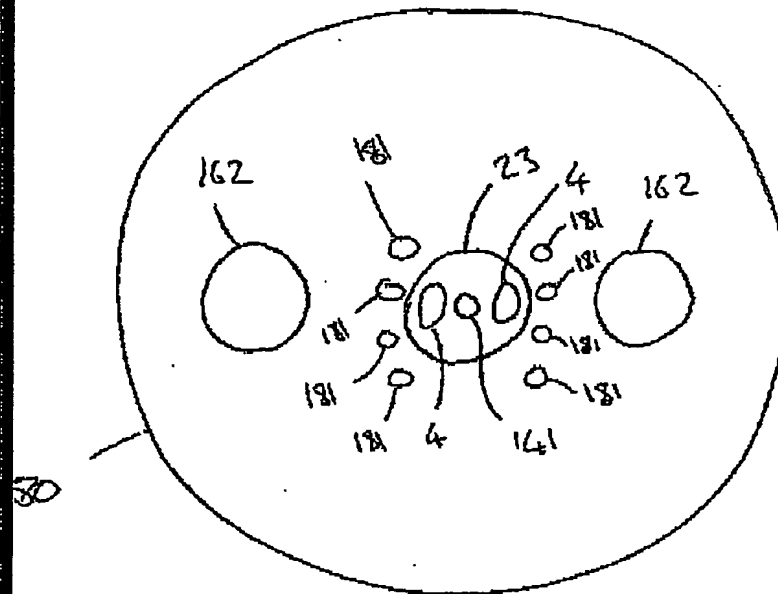


FIG 18

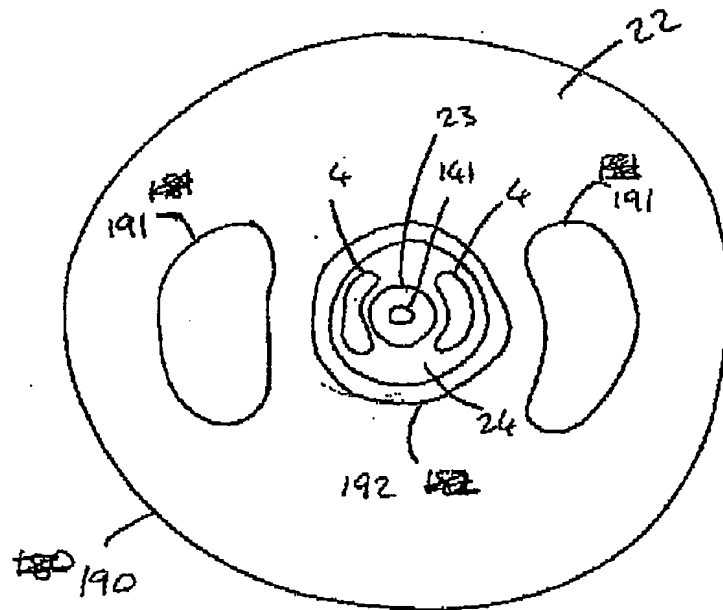


FIG 19

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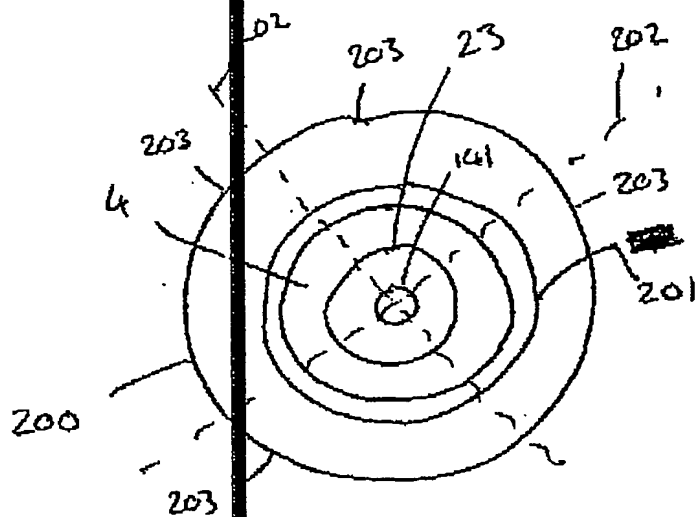


FIG 20

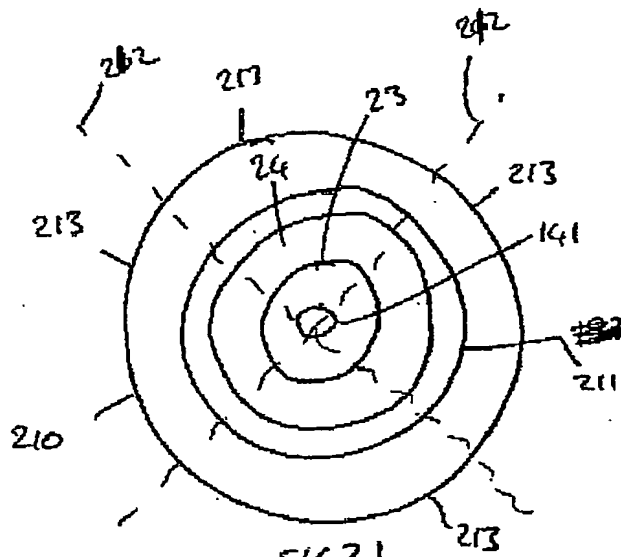


FIG 21

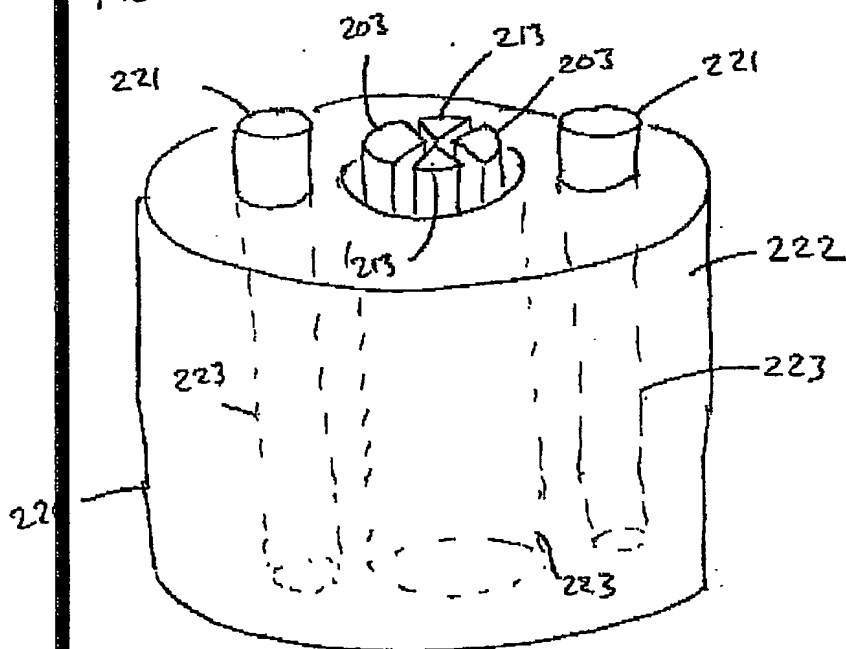


FIG 22

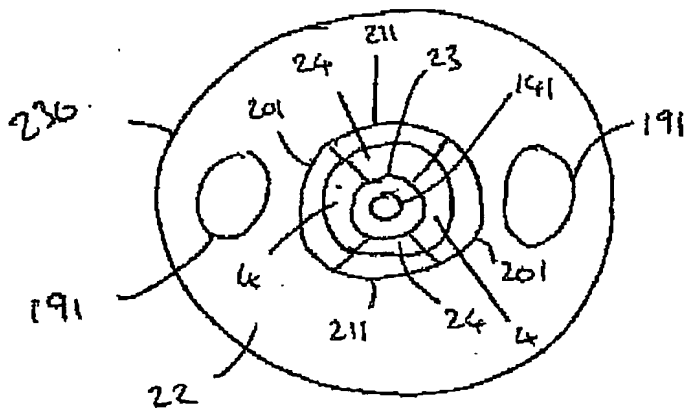
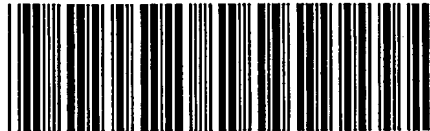


FIG 23

1. The first part of the document is a

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